Quantifying and confirming our understanding of processes controlling stratospheric ozone: Insights from Aura MLS and OMI

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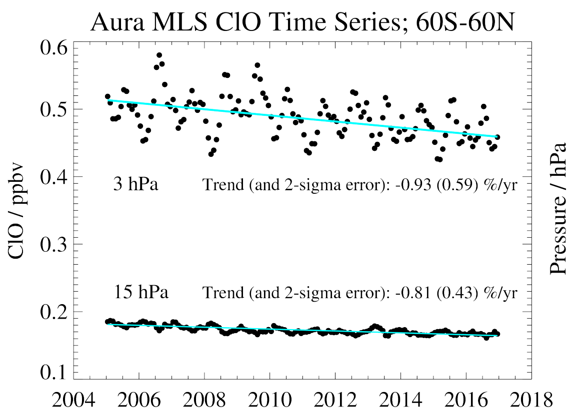
Background and motivation

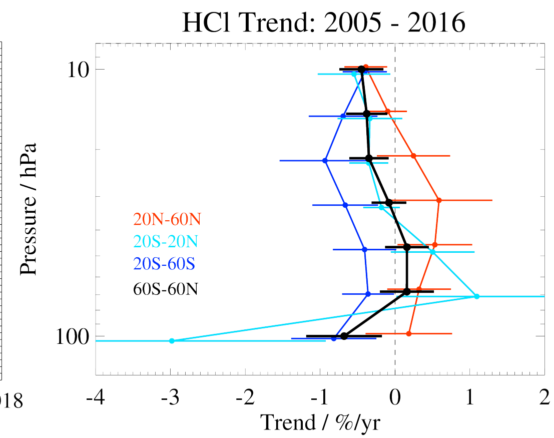
- Conclusive verification that stratospheric ozone destruction is lessening in response to international controls on anthropogenic ozone-depleting substances (ODSs) enacted under the Montreal Protocol and its Amendments remains an atmospheric science imperative
- Indeed, addressing the question "Is the stratospheric ozone layer changing as expected?" is one of Aura's primary science objectives
- Aura has enabled new insights into stratospheric ozone and the chemical and dynamical processes that control it through a combination of factors (and some luck!), including:
  - The extensive suite of measurements of relevance for stratospheric ozone chemistry
    - MLS: vertically resolved profiles of ozone, both the main reservoir form (HCl) and the main reactive form (ClO) of chlorine, the primary components of polar stratospheric clouds (HNO_3 and H_2O), and tracers of stratospheric air motions (N_2O, CH_3Cl, CO)
    - OMI: ozone (total column, profile), various surface UV products, BrO, and OClO
  - The long data record starting shortly after ODS abundances peaked in the atmosphere
  - The remarkable stability of the ozone measurements, with both MLS and OMI exhibiting little or no drift in ozone relative to correlative ground-based observations
  - The broad set of meteorological conditions seen in the polar lower stratosphere of both hemispheres in the years since launch, ranging from exceptional prolonged cold (facilitating severe chemical ozone loss) to strong dynamical disturbances (limiting loss)

A few points before we get started …

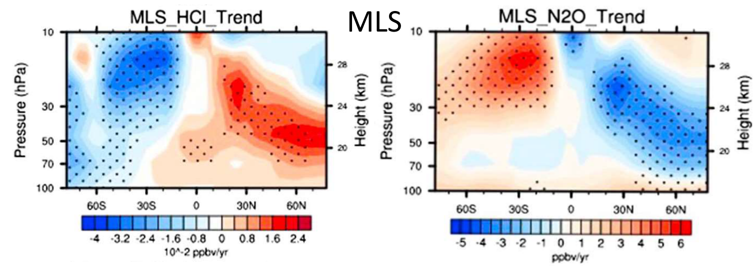
- Disclaimers
  - This is an unapologetically Aura-themed talk and is not meant to be a comprehensive overview of all recent research related to stratospheric ozone
  - Even concentrating exclusively on Aura, however, hundreds of studies on related topics using MLS and/or OMI data have been published; only a few can be highlighted here
  - The emphasis is on more recent work and results (I think are) of most general interest
  - The focus is almost entirely on stratospheric chlorine and ozone
- Outline of the talk
  - Chlorine
    - Extrapolar regions
    - Antarctic lower stratosphere
  - Ozone
    - Extrapolar regions
    - Antarctic
    - Arctic

MLS helps confirm that stratospheric chlorine is declining: Extrapolar regions

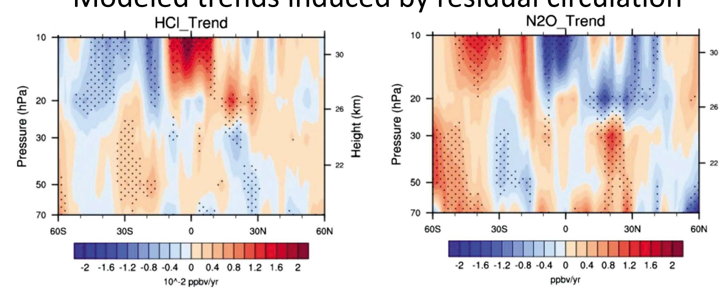




Figures courtesy L. Froidevaux; HCl figure adapted from WMO [2018]



Modeled trends induced by residual circulation

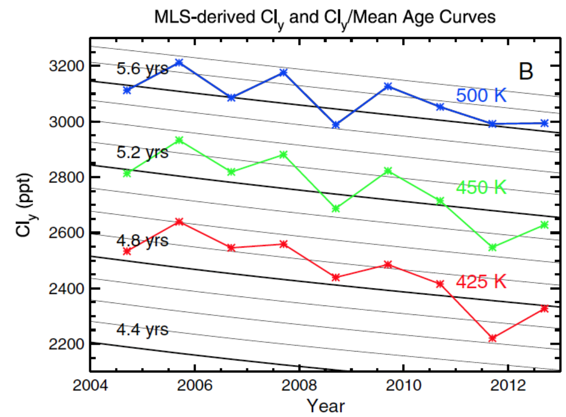


Han et al. [*JGR-A*, 2019]

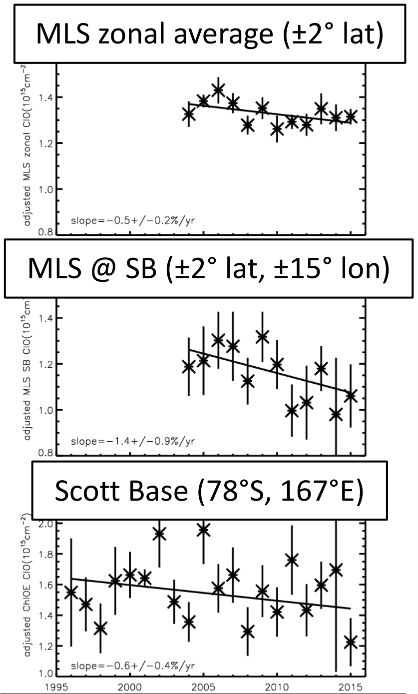
- Near-global (60S–60N) monthly mean **ClO** data indicate statistically significant reductions of ~0.8–0.9 %/yr in the middle and upper stratosphere over the Aura timeframe, consistent with the decline in ODSs controlled under the Montreal Protocol
- However, HCl in the lower stratosphere shows significant hemispheric asymmetries, with decreasing trends in the **Southern Hemisphere** but mostly positive or not significant trends in the **Northern Hemisphere** and the **Tropics**
- Using a chemistry transport model, *Han et al.* [2019] showed that hemispheric asymmetries in the lower stratospheric trends in HCl (and the converse pattern in trend in N_2O, which has opposite vertical and meridional gradients) may arise largely from differences in the trends in the large-scale circulation in the Northern and Southern Hemispheres

MLS helps confirm that stratospheric chlorine is declining: the Antarctic

- *Strahan et al*. [2014] used MLS N_2O to infer the interannual variability in available total chlorine, Cl_y, in the Antarctic vortex
- The MLS-derived year-to-year changes in Cl_y, which arise from variations in stratospheric transport, are 10 times larger than the annual decrease in Cl_y expected from the Montreal Protocol
- At present, interannual differences in the severity of the ozone hole are mainly controlled by temperature, but large dynamically driven variability in Cl_y may also play a role as Cl_y declines further



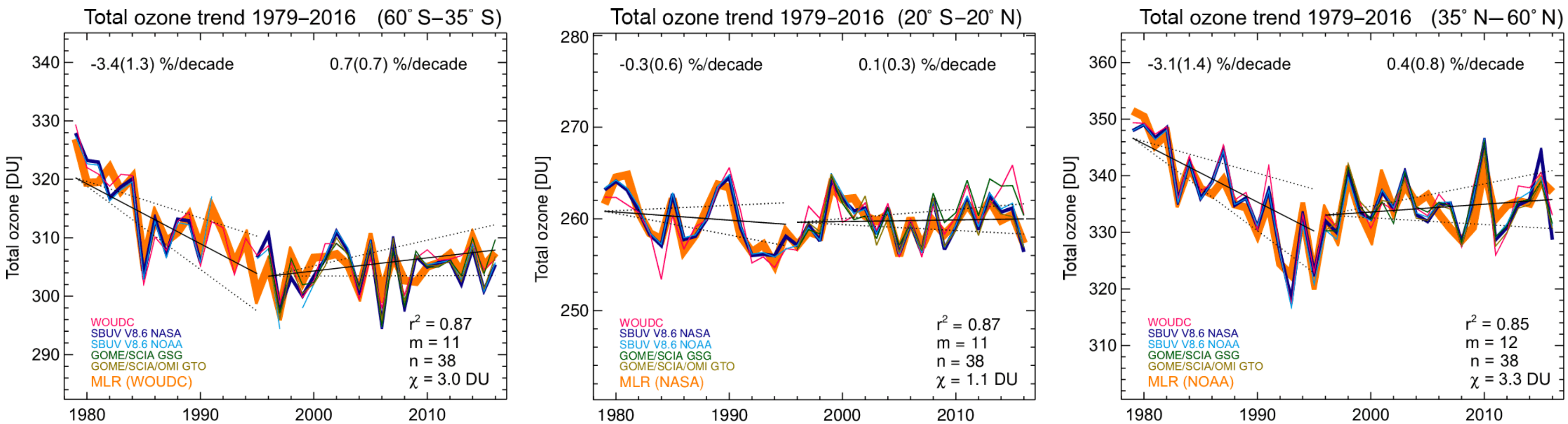
Strahan et al. [*JGR-A*, 2014]



Nedoluha et al. [*ACP*, 2016]

- In the first study to quantify trends in Cl_y over the Antarctic, *Nedoluha et al*. [2016] analyzed 12 years (2004–2015) of MLS and 20 years of Scott Base column ClO measurements collected over the mid-August to mid-September period of peak column ClO values
- The fraction of Cl_y in the form of ClO is sensitive to the presence of polar stratospheric clouds (PSCs), which require low temperatures
- The relationship between annual-average column ClO anomalies and 30 hPa temperature anomalies was used to adjust the column ClO values to remove the effects of year-to-year variations in temperature
- The estimated decrease (0.5–1.4%/yr) in adjusted ClO (a proxy for Cl_y) is consistent with the trend expected from the Montreal Protocol

OMI helps show that no significant trend has yet been detected in global total ozone

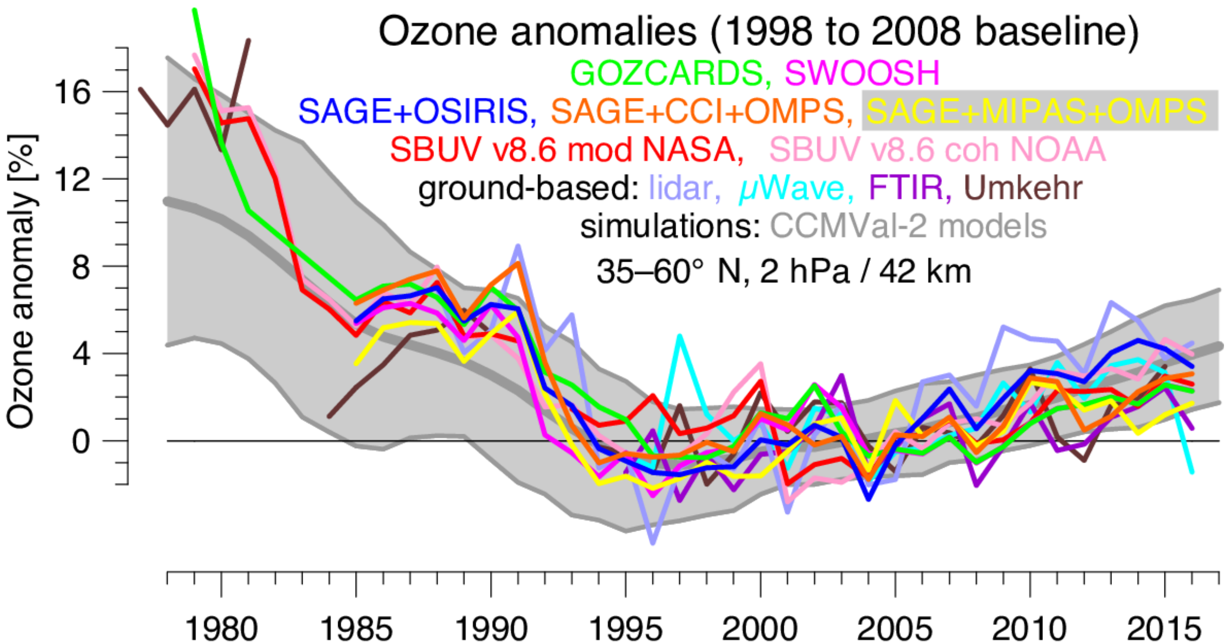


OMI data are central to the "**GTO**" multi-sensor record

Weber et al. [*ACP*, 2018]

- *Weber et al.* [2018] calculated trends by applying a multiple linear regression (MLR) to annual-mean zonal-mean total column ozone from several merged satellite data sets and ground-based observations
- For most data sets and regions, the trends during the post-peak ODS period (1996–2016) are not statistically significantly different from zero; that is, total ozone levels have remained essentially stable in the tropics and extratropics over the last ~20 years
- Positive trends in the Southern Hemisphere midlatitudes are barely significant
- These findings are unsurprising since the year-to-year variability in midlatitude total ozone is large (~5%) compared to the small (~1%/decade) increase expected from ODS phaseout
- Therefore, we are just on the cusp of emerging into the recovery phase

MLS helps show that upper stratospheric ozone is recovering



Aura MLS data are central to the "**GOZCARDS**" and "**SWOOSH**" multi-sensor records

Steinbrecht et al. [*ACP*, 2018]

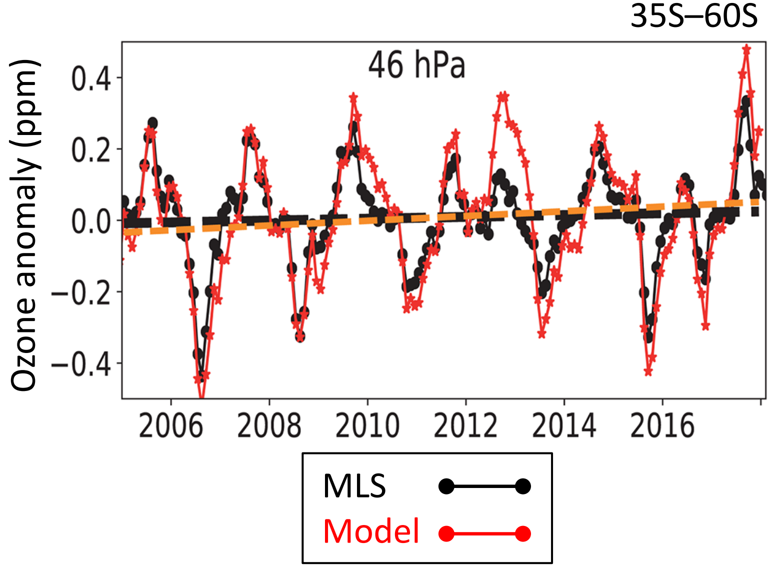
- Annual-mean ozone anomalies (relative to 1998–2008 climatology) from multiple merged satellite data sets and ground-based observations reveal statistically significant increases in the extrapolar upper stratosphere of 1–3% per decade since 2000 [*Steinbrecht et al.*, 2018]
- The upward trend is largest in northern midlatitudes at ~40 km (2 hPa)
- Below 35 km, 2000–2016 ozone trends are smaller and not statistically significant
- Models attribute about half of the observed increase to ODS decline and the other half to GHG-induced upper stratospheric cooling (which slows gas-phase ozone destruction)

MLS shows the need for continued vigilance in the lower stratosphere

- *Ball et al.* [*ACP*, 2018] confirmed the recovery of ozone in the upper stratosphere but presented evidence from MLS that lower stratospheric near-global (60N–60S) ozone continued to decline over the 1998–2016 period

- However, in a follow-up to that study that also used MLS data, *Chipperfield et al.* [2018] found that, following a large negative anomaly in 2016, much of the apparent decrease at extrapolar latitudes was reversed by a sharp increase in lower stratospheric ozone in 2017

- Thus, including one additional year in the observational time series altered the picture from one of an ongoing downward trend to one of strong interannual variability



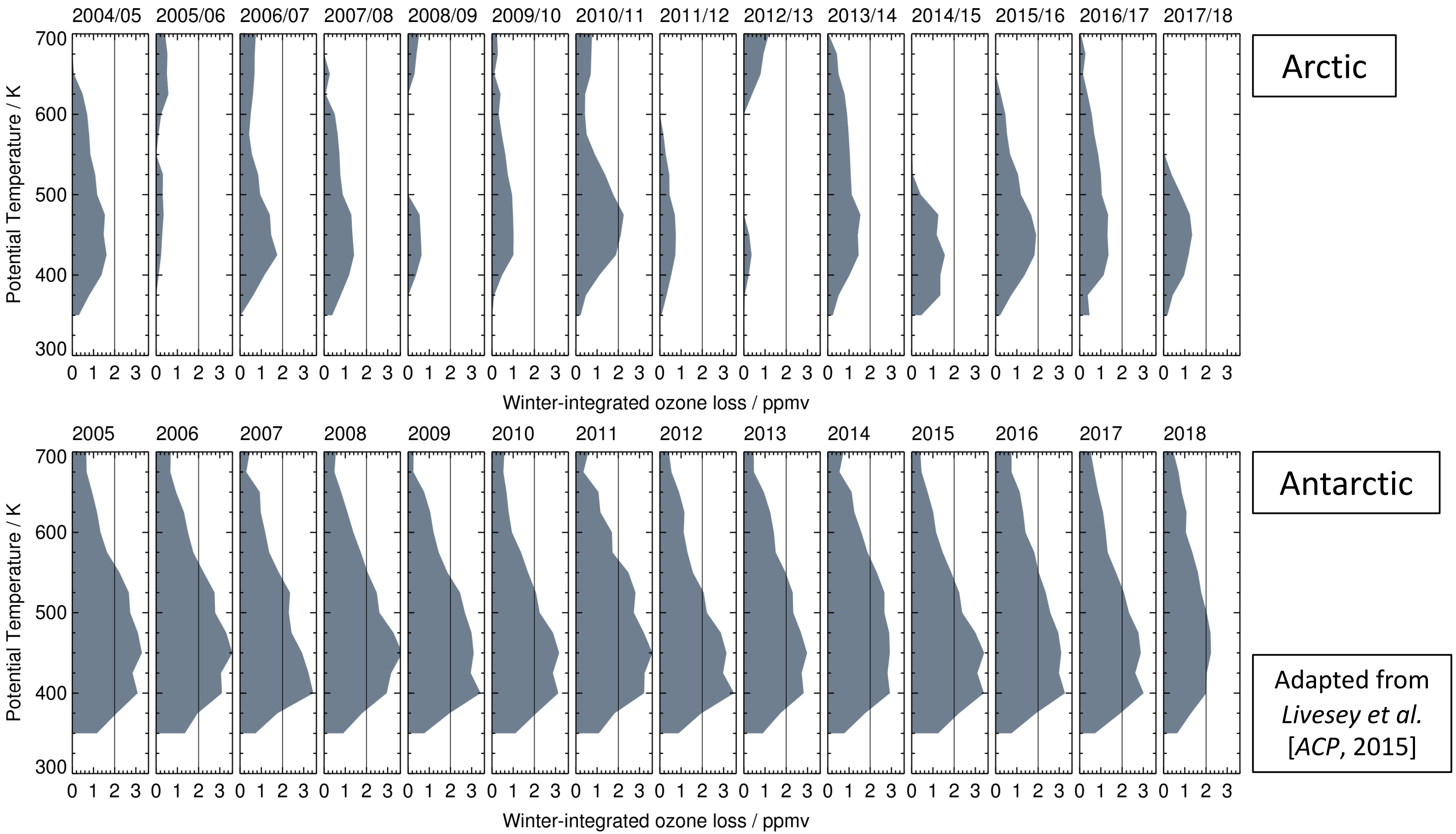
Chipperfield et al. [*GRL*, 2018]

- The variability observed by **MLS** is captured well by 3D chemical transport **model** simulations; tests showed that, on multiannual timescales, variations in extrapolar lower stratospheric ozone are driven mainly by atmospheric dynamics rather than chemistry

- These results underscore the importance of continued monitoring of ozone profiles; as the 2018 WMO Scientific Assessment of Ozone Depletion stated: “longer records are needed to robustly identify trends in this region”

MLS quantifies chemical ozone destruction in the polar lower stratosphere

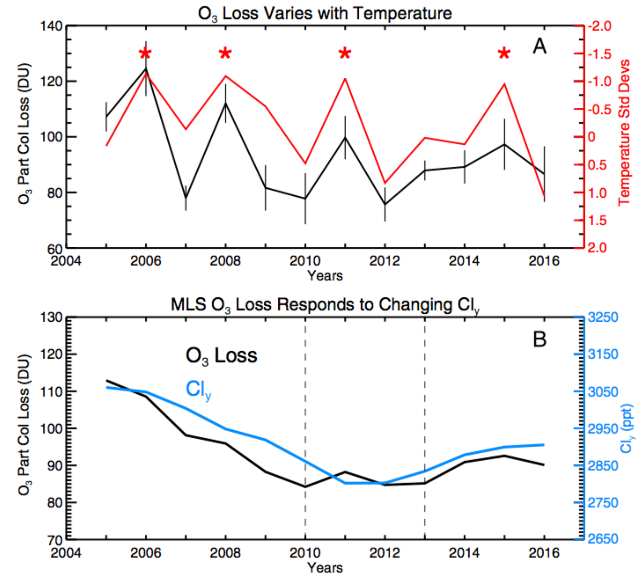
- The Lagrangian "Match" technique accounts for transport effects by measuring changes in ozone between two observations of the same air mass, thus quantifying the chemical loss
- Profiles of cumulative chemical ozone loss show strong interannual variability in the Arctic
- In the Antarctic, loss is much larger, deeper, and more uniform from year to year



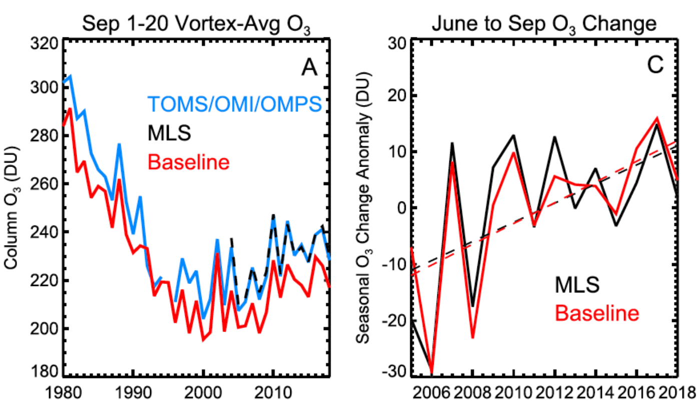
Adapted from *Livesey et al.* [*ACP*, 2015]

MLS shows hints of recovery in the Antarctic ozone hole

- An Antarctic ozone hole continues to occur every year, with the severity of **O_3 loss** strongly modulated by **temperature**
- To try to mitigate dynamical effects, *Strahan & Douglass* [2018] calculated loss as the difference between MLS vortex-averaged partial column (216–12 hPa) ozone in early (1–10 July) and late (11–20 September) winter
- Temporally smoothing the estimated **O_3 loss** yields behavior over 2005–2016 that echoes changes in MLS-derived **Cly**
- Simulations from a chemistry transport model show a similar evolution, in line with expectations of recovery



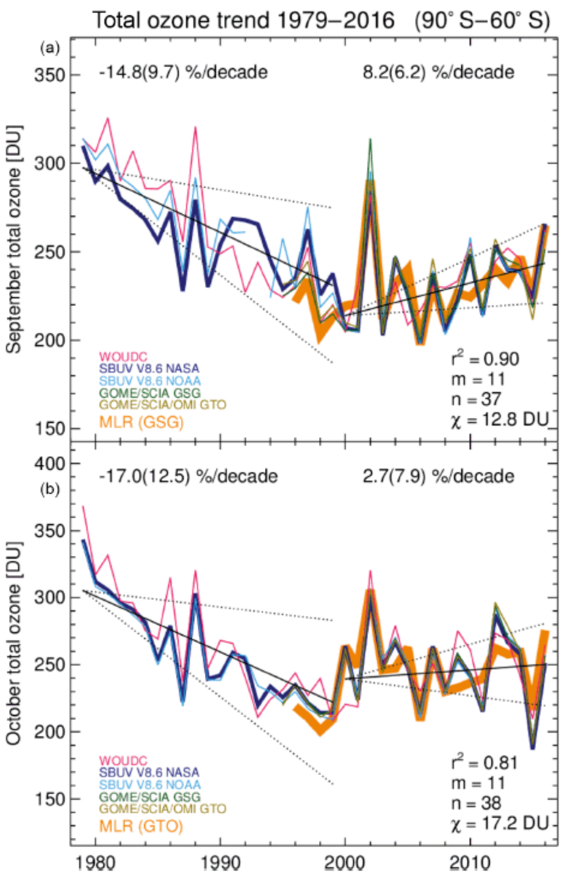
Strahan and Douglass [*GRL*, 2018]



Strahan et al. [*JGR-A*, 2019]

- September vortex-averaged column O_3 in the **model** tracks the variability observed by **TOMS/OMI/OMPS** and **MLS** (+ model tropospheric column), which are in excellent agreement [*Strahan et al.*, 2019]
- **MLS** and **model** year-to-year variations in the change in vortex column ozone between June and September (with 14-yr mean removed) agree well
- Both MLS and the model indicate a ~20 DU reduction in ozone depletion over the Aura period

OMI shows hints of recovery in the Antarctic ozone hole (Part I)



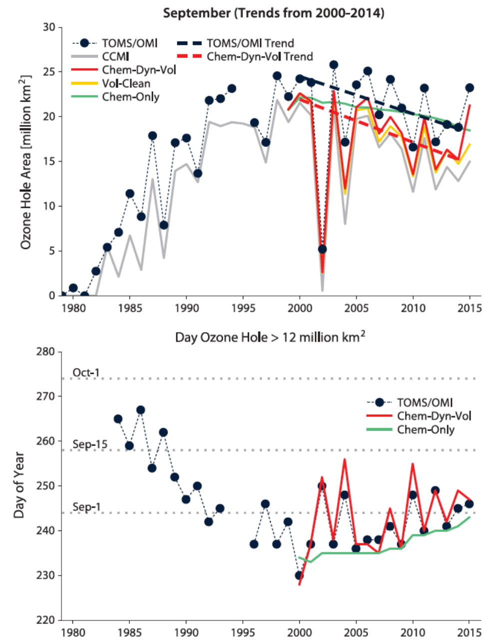
Weber et al. [*ACP*, 2018]

OMI data are central to the "**GTO**" multi-sensor record

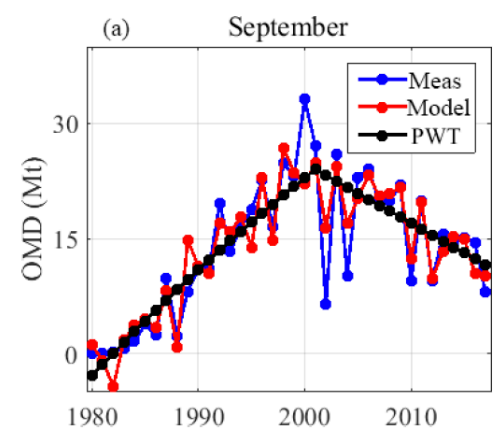
- *Weber et al.* [2018] also applied MLR to monthly mean polar total column ozone, again using several merged satellite data sets and ground-based observations
- In September the post-ODS peak (2000–2016) trends are barely significant at ~8–10 %/decade (~1–2 DU/yr)
- *Weber et al.* noted that changes in the regression model, use of different explanatory variables, etc. can easily render the results not statistically significant
- Also, because of the large dynamical variability in October, trends for that month are much smaller and not statistically significant
- Using a different MLR model and the multi-sensor reanalysis MSR-2, which provides global assimilated total ozone fields based on 14 satellite data sets, including OMI, *Pazmiño et al.* [*ACP*, 2018] found statistically significant trends in ozone in September of ~1.8–2.8 DU/yr over the 2001–2017 period
- *Pazmiño et al.* were the first to report significant ozone trends for the 15 September – 15 October interval of maximum ozone depletion (~1.2–2 DU/yr)

OMI shows hints of recovery in the Antarctic ozone hole (Part II)

- Ozone Hole Area (OHA)
  - *Solomon et al.* [2016] calculated the area inside the 220 DU contour in monthly averaged September **TOMS/OMI** data and found shrinkage of 4.5 million km^2 from 2000 to 2015
  - They also found that the day of the year on which the ozone hole exceeds a certain area has been occurring later in recent years, such that early September holes are becoming smaller
  - Using TOMS/OMI/OMPS and model results, *Strahan et al.* [2019] concluded that trends in OHA are best computed by averaging the daily areas of O_3 < 220 DU in September, which produces a slower trend than September-mean-O_3 < 220 DU
- Ozone Mass Deficit (OMD)
  - *Pazmiño et al.* [2018] also applied **MLR** to daily mean **MSR-2** values of OMD – the difference between the actual ozone column and a reference column of 220 DU – and calculated a negative trend (~0.6–0.9 Mt/yr) from 2001 to 2017 in both the September and 15 September to 15 October periods
  - These results are in good agreement with OMD trends reported previously by *de Laat et al.* [*ACP*, 2017], also based on MSR-2



Solomon et al. [*Science*, 2016]

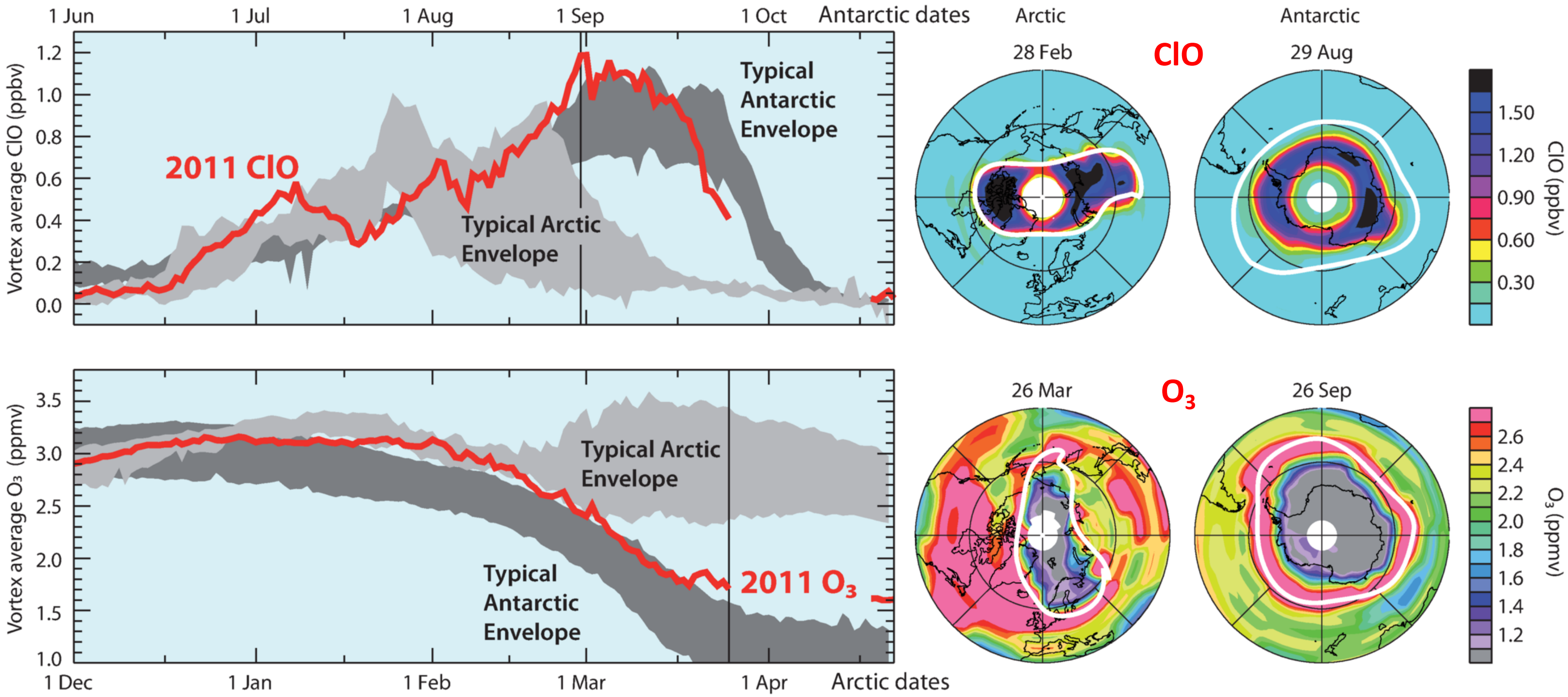


Pazmiño et al. [*ACP*, 2018]

MLS observed unprecedented Arctic ozone loss in 2011

485 K, ~19 km

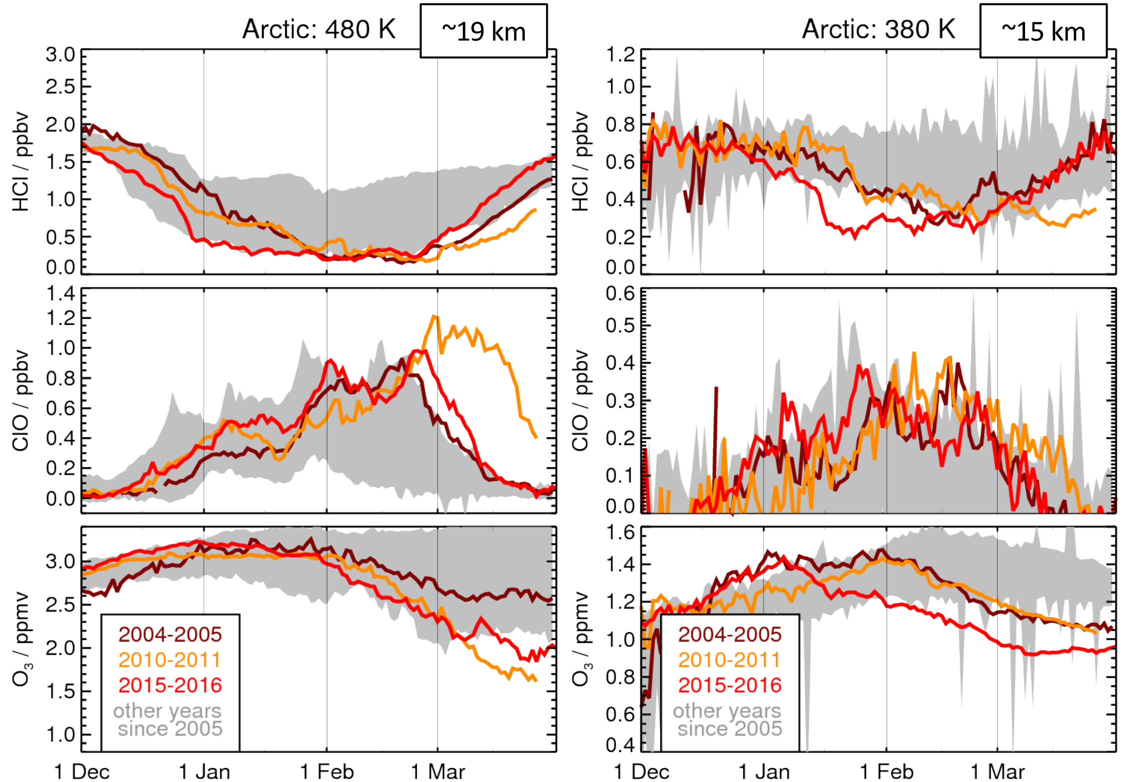
Adapted from *Manney et al.* [*Nature*, 2011]



- Minimum temperatures were below the chlorine activation threshold for a longer time and over a deeper vertical region in 2010/2011 than in any other Arctic winter on record
- ClO enhancement in 2011 was much more intense, extensive, and prolonged than in any other cold Arctic winter observed by MLS, with peak ClO abundances starting to decline rapidly only ~1 week earlier than typical in the equivalent season in the Antarctic
- An unprecedented degree of chemical ozone loss, coupled with atypically weak transport into the lower stratospheric vortex, led to exceptionally low springtime ozone (though ozone values remained higher and the low-ozone region smaller than in the Antarctic)

MLS measurements highlight the large degree of interannual variability in the Arctic

- The **2015/2016** winter was also extraordinarily cold, with strong chlorine activation and lower stratospheric (~19 km) ozone values comparable to or slightly below those in **2010/2011** through much of the winter [*Manney and Lawrence*, 2016]
- But chemical processing halted about a month earlier than in 2011, preventing record ozone loss
- *Johansson et al.* [2019] used MLS to place airborne data from a 2016 field campaign into context



Adapted from *Manney and Lawrence* [*ACP*, 2016]; *Johansson et al.* [*ACP*, 2019]

- MLS data revealed exceptional conditions in the lowermost stratosphere (380 K, ~15 km), with unusually low HCl and strongly enhanced ClO, leading to large depletion (~0.4 ppmv); although overall loss was larger in 2011, lower ozone values were reached at 15 km in 2016
- The very low ozone values resulted in abnormally rapid reformation of HCl at winter’s end
- Large dynamically driven variability precludes detection of significant trends in the Arctic

Summary and perspective

- Together, measurements obtained by Aura MLS and OMI have provided a comprehensive view and enhanced our understanding of the dynamical and chemical processes controlling stratospheric ozone
- The 15-year Aura data record is just now becoming long enough to permit the signature of ozone recovery to be detectable against the backdrop of large natural variability
- Lessons learned:
  - Despite a multi-decade measurement record, the stratosphere continues to display previously unobserved behavior on a regular basis – although some years are more interesting than others, no year is "average"!
  - Each additional year of measurements enhances the value of the Aura record

2019
ozone hole
in progress